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REPORT ON PRECIPITATION

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1. INTRODUCTION

'What happens to the rain' is without a doubt the shortest definition of the science of hydrology. 'The rain and what happens to it' is probably more apt and a definition that demonstrates better the importance of this flux. This importance is, of course, generally recognised, both nationally and internationally. Apart from the work of the International Association of Scientific Hydrologists and its Committee on Precipitation, there are those activities stemming from the several resolutions adopted by the Coordinating Council of the International Hydrological Decade. Some of these resolutions have been taken up by the World Meteorological Organisation which has working groups of its own that are active on a variety of problems concerned with precipitation. National IHD programmes include studies of precipitation, measurement, network design, frequency of intense rainfall and assessment of probable maximum precipitation. Outside the IHD, work on precipitation is being carried out in a variety of disciplines; ecologists are studying the nutrient supply in rain, the occurrence of heavy rain during the sheep breeding season is of interest in animal

husbandry studies, hail and its suppression are vital to viticulture, while communications engineers are investigating how precipitation interferes with the propagation of microwaves. The field is vast and not one that can be covered adequately in a few pages, hence this report concentrates on subjects that are considered most central to hydrology. Topics of a specialised nature, or ones involving an allied discipline, are not included, such as radar measurement of rainfall (Kessler and Wilk 1968), rainfall stimulation (Neiburger 1969), time series analysis (Sneyers 1964), rainfall simulation (Grace and Eagleson 1966, Raudkivi and Lawgun 1970) and inadvertent rainfall regime modification (Changnon 1969).

2. MEASUREMENT AT A POINT

Although the subject of precipitation measurement has a long history and a voluminous literature (Kurtyka 1953, Israelsson 1967), awareness of the significance of the conventional type of instrument's shortcomings has grown only during recent years. It is now being recognised that measurements of precipitation, particularly rainfall, are neither reliable nor accurate and that hydrologists have been misled in assuming that they are.

2.1 RAINFALL MEASUREMENT

Large numbers of comparisons of different types of raingauge have been undertaken at various sites (Poncelet 1959a, Jaquet 1960, McGuinness & Vaughan 1969) and there has also been an international comparison based on the interim reference precipitation gauge (Poncelet 1959b, WMO 1969). Different sizes of gauge (Kalma *et al.* 1969) and different shapes (Maidens 1965) have been tested. Rain-gauge readings have been compared with lake level measurements (Harbeck & Coffay 1959, Kkarbaum & Klinker 1966) and lysimeter records (McGuinness 1966) and have been found too low. However, recognition that the chief source of error, namely wind, causes the normal type of elevated gauge to under-register in a systematic fashion has led to the use of the pit gauge (Struzer *et al.* 1965, Rodda 1967). This instrument, which is particularly suited to the measurement of rainfall is being used in a new WMO international

programme of raingauge comparisons.

2.2 SNOWFALL MEASUREMENT

The effect of wind on a gauge is even larger in the case of snowfall, resulting in greater difficulty in obtaining more nearly true measurements of snowfall than rain. It has been estimated from the water balance in one region where snow is a very important component of precipitation, that there is a systematic annual error of about 20% in the assessment of precipitation (Findlay 1969). Snow gauges in sheltered surroundings are employed as reference instruments in some countries (Uryvaev *et al.* 1965), while the profile method, which uses pairs of gauges at different levels, one shielded and the other unshielded, has been tried in others (Hamon 1970). Measurement of snow on the ground is of course much simpler than catching snow as it falls, but this too has its problems (McKay 1968). The use of snow courses and the sampling of cores are well known techniques, as are devices like snow platforms and snow boards. Radioisotope gauges have been employed in remote areas and these are often telemetering, while neutron scatter devices have been employed for snow density determinations (Danfors *et al.* 1962). The technique of measuring the attenuation of the natural radioactivity of the soil by the snow lying on it has been developed for determination of snow depth (Zotimov 1965) and now aircraft are being used for these surveys (Dahl and Odegaard 1970, Peck *et al.* 1970). The snow pillow, despite its draw-backs (Beaumont 1968), seems to be the instrument that provides the best information on the timing and amount of snow and is now in use at a number of sites (Engman 1966, Tollan 1970), some with telemetering facilities (Shannon 1968). A possible alternative is the snow melt lysimeter. An instrument for snow, equivalent to the pit gauge, has yet to be devised however, while techniques for the measurement of hail (Voronov 1967), dew and the other minor forms of precipitation have to surmount even more difficult problems.

2.3 SOURCES OF ERROR

Aerodynamically designed gauges (Poncelet 1962), some developed from wind tunnel tests (Robinson & Rodda 1969), are a possible alternative to pit gauges, but there is the problem of how to obtain a performance that is reasonably constant for all combinations of turbulent wind flow with different drop size spectra. There are, of course, other sources of error that affect a gauge. Splash-in has been investigated (Struzer & D'jackova 1966, Struzer *et al.* 1968) together with the lateral travel of splashes determined in the field (Green 1969, Green 1970). The loss due to wetting of the funnel of certain types of gauge has also been assessed (Necaev 1965) and a correction made for evaporation of the collected water (Golubev 1960).

2.4 CORRECTING FOR ERRORS

As a consequence of these studies of gauge errors, some countries have adopted a new type of gauge for their national networks (Beaak 1945, Struzer 1965b), while countrywide maps have been constructed to show how the difference between precipitation at gauge height and at ground level is distributed (Struzer *et al.* 1968, Rodda 1970). Few attempts have been made to assess the precipitation over the world's oceans, regions where gauge errors would probably be even greater than for the most difficult land areas.

2.5 AUTOMATIC AND OTHER INSTRUMENTS

A number of new types of recording raingauges have been devised such as the one with a measuring chamber drained by a magnetic valve (Karkunen 1965) and instruments are available commercially that record on punched paper tape or magnetic tape. In addition, vecto-pluviometers continue to be employed at a number of sites (Meyburgh

& Wicht 1966), while more specialised devices have been produced, such as the one for determining raindrop size (Joss & Waldvogel 1967). Some indirect methods of measurement of precipitation have also been devised, such as by use of optical attenuation (Warner & Gunn 1969) and by capacitance changes (Semplak 1966), but their weakness is that they rely on bucket-type gauges for their calibration.

3. NETWORKS

The majority of precipitation networks have developed in a haphazard fashion and few are adequate in terms of density of instruments and length of records. There was, however, a symposium on the Design of Hydrological Networks in Quebec in 1965. There are also available a number of comprehensive reports on networks such as those published by WMO (Kohler 1958, Rodda *et al.* 1969) and a number of accounts of the design and operation of networks in individual basins (Hamilton 1954, Wicht *et al.* 1969). Although some papers deal with network design for snow depth determinations (Hegedus & Szesztay 1967, Orstrem & Stanley 1969), the majority are concerned with rainfall. Naturally there are differences between network designs according to objectives, for example, flood warning as opposed to surveying water resources. Most networks, however, must be classed as multipurpose, but whichever objective is paramount, the problems of design are similar. These problems may be stated as follows:

- i. How many stations are required?
- ii. Where are the stations to be located?
- iii. How long should they operate?

There are a number of objective methods of answering the first question, fewer ways of replying to the second, and hardly any means of deciding when stations should cease operating. In addition

there is the need to translate the information content of the data into its economic worth - a subject rarely treated.

3.1 NUMBER OF GAUGES

There are various methods of analysing the rainfall records from a network to derive a parameter, such as the variance, then relating that parameter to the number of gauges, and the required accuracy of estimate of the mean (Rycroft 1949, McCulloch 1961, Panchang and Narayanan 1962, Sutcliffe 1966, Stephenson 1967, Herbst & Shaw 1968). A variant of this approach is to 'saturate' a basin with gauges and to compute the error that results from employing only a small number of the gauges (Huff & Neill 1957, McGuinness 1963, Nicks 1965). This approach assumes, of course, that the true mean basin rainfall is given by the dense network - a questionable assumption.

3.2 SPACING OF GAUGES

The spacing or location of raingauges is dealt with in other papers, the use of correlation analysis being favoured recently, (Hershfield 1967, Holland 1967). Networks in different areas and different periods of observations in the same network have been investigated in terms of the decay of correlation between gauges. Factors other than distance between gauges, such as altitude differences, have also been considered (Hutchinson 1969). The use of primary and secondary stations is advocated as a method of establishing spatial patterns more readily and the optimum duration for secondary stations has been assessed (Langbein 1960). It has been postulated however, that some of the apparent variability of rainfall across small areas may be due to the exposure of raingauges (Hamilton 1954) and to faults in the performance of the gauges themselves (Rodda 1970). The various mathematical models of basins that have been developed to predict runoff might be optimised on the hydrological network rather than on

the runoff, particularly the rainfall network, so that the minimum error would result. Alternatives are the use of spectral analysis (Eagleson & Shack 1966) and sampling theory (Eagleson 1967). Another approach is to calculate the standard error of the mean basin rainfall using a covariance factor amongst raingauges, to use a Lagrangian multiplier technique to minimise the variance and to optimise allocations of gauges (Sun Fu Shih *et al.* 1970). However, all these methods require data from networks of gauges that have been in existence for some time. No method has yet been devised that will permit determination of the number of gauges required for a basin which has no records.

3.3 SPECIAL NETWORKS INCLUDING THROUGHFALL NETWORKS

Basin scale and countrywide networks are not the only ones that have received attention; there are the special purpose networks covering small areas that are designed for sampling the variations in the chemical composition of rainfall for example, Andersson 1969, while throughfall networks are an integral part of studies of the distribution of interception. The following extract from a review of the subject by Leyton and Rodda (1970) covers many of the important points.

"The problem of sampling a variable throughfall is discussed in some detail by Reynolds & Leyton (1963) and Leyton *et al.* (1967), (1968). The aim is usually to obtain a reasonably reliable estimate, generally one with a mean standard error of about $\pm 5\%$ with a minimum number of measurements. The need for some statistical measure of the reliability of these measurements has not always been appreciated so that many of the results that have been quoted for interception are of questionable reliability. Various types of collecting gauges have been used ranging from large troughs to small standard type raingauges. The theoretical advantage of troughs is that because they sample more of the throughfall fewer are needed. Eidmann (1959) and others used very long narrow troughs capable of sampling below the crown spread of adjacent trees; Stalfelt (1963) preferred triangular troughs. Reynolds & Leyton (1963) have described automatic recording techniques based on

"tipping bucket gauges" and electromagnetic counters that considerably simplify the problems of collecting and measuring the relatively large quantities of water involved.

There are various ways of increasing the accuracy of the estimates without increasing the number of gauges. The gauges can be moved to new random positions after every storm (Wilm 1943, Hoover 1953, Law 1957) or a combination of fixed and movable gauges can be used (Wilm 1946, Reilly *et al.* 1969). If there is a systematic pattern of throughfall, for example, a substantially linear increase in throughfall with distance from the tree stem, the number of gauges can be reduced by stratifying, i.e. sampling specified zones below the crown (Kettredge *et al.* 1941) or by taking into account the regression of gauge catch on the relative distance from the stem (Reynolds & Leyton 1963)."

4. AREAL RELATIONS

Perhaps the division between network design and the relationship between point and areal assessments is rather arbitrary, but there are some studies which concentrate more on the latter topic.

4.1 POINT TO AREA RELATIONS

The storm point rainfall to storm areal rainfall relationship, which has been investigated frequently, falls best into this second category, although of course, the form of the network is an important consideration even here. Formulae for characterising these area-depth relations were summarized by Court (1961) and there are other examples of this type of study (Burns 1964). Models describing the distribution of rainfall in convective storms have been devised for the Southwestern United States (Fogel & Duckstein 1969, Fogel & Duckstein 1970) and some particularly valuable investigations have been made in Illinois (Huff & Neill 1957, Huff 1966) where in addition, longer period rainfalls have been considered

(Huff & Shipp 1969). Here correlation analyses were also undertaken to depict the decay in association with increasing distance from a central gauge and this was repeated for different sizes of networks. Similar studies have been carried out in the Soviet Union, where the representativeness of single gauges has been linked to the accuracy of computing the mean from a network (Kagan 1966, Kagan 1967), Guscina *et al.* 1967, Poliscuk 1967). Other studies have been concerned with how to use these correlation techniques for areas with sparse networks (Hutchinson 1969). Where a dense network exists, relationships have been examined between the basin mean, calculated from all the gauges, and the same quantity determined from a few key gauges (Andersson 1968, Collinge & Jamieson 1969), so that these few sites might be equipped with telemetering gauges for flood forecasting purposes. In another study of storm rainfalls, rain recorders were used in conjunction with radar echo observations to investigate distribution patterns (Amorocho *et al.* 1967). A similar investigation (Amorocho & Brandstetter 1967) was concerned with the three parameter gamma distribution and low order polynomials for temporal and spatial fitting of rain recorder records as an aid to the analysis of data from a network.

4.2 ASSESSMENT OF MEAN BASIN RAINFALL

The technique of fitting a surface to rainfall data has also been applied for studies of quite large areas (Solomon *et al.* 1968, Unwin 1969) for small basins (Mandeville & Rodda 1970, Chidley & Keys 1970) as an alternative to the traditional methods of assessing the mean basin rainfall.

The techniques of determining the average depth of precipitation over a basin have been reviewed a number of times (Whitmore *et al.* 1962, Corbett 1967, Rainbird 1967). Several variations of the regression analysis type of approach (Rodda 1962) have been tried (Dawdy & Langbein 1960, Peck & Brown 1962, Sutcliffe & Carpenter 1967, McCulloch & Booth 1970) and mean basin precipitation has even

been assessed as the sum of runoff and evaporation for areas without adequate networks of gauges (Wallen 1968). Computer programs have been devised for assessment of mean basin precipitation in a number of different ways (Akin 1971) and the accuracy of assessing the mean has also been explored (Hutchinson 1970) using time series analysis.

4.3 RELATIONSHIPS OVER SMALL AREAS

Attention continues to be given to the relationship between rainfall and topography in various parts of the world. Detailed studies of distribution over a number of small areas have also been made, particularly in Project Pluvius (Andersson 1963, 1964) and in later Swedish studies (Sandborg 1969, 1970) using rain-gauges installed level with the ground. The coefficient of variation was employed to describe differences across the area being investigated in the earlier papers and for the later ones, in conjunction with the origin of the rain and wind direction. In another study (Sharon 1970) rainfall distribution across a small catchment in the Negev was assumed to be complicated by the effect of wind on the gauges that were employed.

5. SPACE-TIME ANALYSES

A great number of analyses of precipitation records have been undertaken for single stations, and for basins, countries and even continents. National precipitation atlases are available for certain countries and regional atlases are being prepared under the auspices of WMO's Regional Associations. Much of the information in these atlases consists of annual, seasonal, monthly and weekly means, but more specialised analyses are available for some countries. Quite a lot of attention has been given to the extremes - high intensity rainfall and drought, while time series have been examined for evidence of climatic change. By far the biggest gap

in knowledge relates to rainfall over the oceans, for present techniques (Tucker 1961) are virtually limited to the use of reports of past and present oceanic weather for the assessment of amount and there is no information on intensities, frequency of rain and other characteristics.

5.1 INTENSE PRECIPITATION

Probable maximum precipitation (PMP) studies have been conducted for various parts of the world but particularly for the United States. Generalised estimates of PMP have been computed, on the one hand for the halves of a complete country (U.S.W.B. 1960) and on the other for much smaller areas (Singleton & Helliwell 1969). The evolution of methods for estimating PMP have been reviewed (Myers 1969) and the concept severely criticised (Yevjevich 1968), while an alternative to the physical approach has been devised (Hershfield 1961). This method is based on the use of the largest amounts of rainfall ever recorded and has been employed in several areas (McKay 1968) while the cataloging of large amounts continues nationally (Bleasdale 1963, Colenbrander & Verstraate 1967) and internationally (Paulhus 1965).

Frequency studies of intense rainfalls for different durations have been undertaken in various parts of the world. The rainfall frequency atlas of the United States (Hershfield 1966) is one of the best examples of this type of work, but there are similar studies from contrasting regions, for example, those by Reich (1963) and Lockwood (1967). Other studies have been undertaken of rainfall characteristics that can be used for design purposes (Smirnova 1967, Pilgrim *et al.* 1969) and studies have been made of the distribution of rainfall in time during heavy storms (Huff 1967), in terms of the probability of certain amounts occurring within particular periods during the storm. Comparisons have been made of the different extreme value fitting procedures (Alexander *et al.* 1969, Alexander 1970). Of course, these special studies

are usually concerned with point samples and these are often assumed to be uncorrelated when in fact a storm occupies a finite area. One attempt to introduce three dimensions into rainfall frequency studies (Alexander 1969) employs the idea of a storm mosaic for use in mathematical models of areal rainfall.

5.2 DROUGHT AND LONGER PERIOD RELATIONS

Studies of drought, as defined by absence of rainfall, have been carried out for descriptive and predictive purposes for various parts of the globe. Several reviews of the whole field of drought have been or are being undertaken (Subrahmanyam 1967). The probability of precipitation amounts falling short of a given quantity, such as the mean, has been determined for a number of areas and is expressed in map form (Shaw *et al.* 1960, Gibbs & Mather 1968) or as tables (Coligado 1969), or graphs (Bleasdale 1969). Such studies are of course particularly valuable for water resources purposes and in determining irrigation practices. One problem with these approaches is that drought exhibits persistence. At certain sites, there is a tendency for the observed number of long dry periods to exceed the number predicted by theory, for example by binomial theory (Brooks & Carruthers 1953) and one Markov model (Weiss 1964), although another Markov model (Watterson & Legg 1967) and a random model (Fitzpatrick & Krishnan 1967) was found to produce an improved fit. Sequences over longer periods have also been examined to discover, if for example, the weather of one month is independent of another (Murray 1967, Stephenson 1967). No evidence was forthcoming, however, which justified assumptions about the nature of successive periods of weather being compensatory, i.e. a wet winter being followed by a dry summer. Seasonal amounts of rainfall and their distributions have also been examined by harmonic analysis (Fitzpatrick 1964, Hastenrath 1968).

6. PROSPECT

None of the other networks of hydrological instruments can match those employed for assessing the distribution of precipitation in terms of number of gauges and length of records. No other records are used so extensively, not only in hydrology but also in allied fields. No other records are as readily accepted as being correct when in fact they are not. This problem of measurement is but one of the points that remains to be solved (where precipitation is concerned) but should a gauge be devised that will provide a measure of the amount of water reaching the ground to a known degree of accuracy, then the solution of most of the other problems should be made simpler. Some of the topics that continue to demand the attention of research workers have been mentioned already and these and others are listed:

6.1 MEASUREMENT AT A POINT

- (1) Improvement of observer read gauge methods of measuring
 - (a) rainfall
 - (b) snowfall
 - (c) other forms of precipitation to produce observations to a known degree of accuracy.
- (2) Development of reliable automatic instruments for recording (a) (b) and (c) preferably employing magnetic tape, that can operate unattended at remote sites for long periods.

6.2 NETWORKS

- (1) Provision of an objective method of network design that will allow determination of numbers of gauges, their spacing and how long the network should operate for the following ranges of conditions

- (a) for time periods from a few minutes to a year
- (b) for basins of sizes ranging from small urban areas to major rivers
- (c) for the various meteorological conditions
- (d) for the different types of topography

6.3 AREAL RELATIONS

- (1) Development of methods for determining the average depth over a basin, particularly methods that are appropriate for computer use and ones that are suitable for hydrological modelling.
- (2) Improvement of methods for characterising the distribution and depth of rain in storms, including use of radar.

6.4 SPACE TIME ANALYSES

- (1) Further investigations of methods of assessing PMP
- (2) Development of fitting procedures for extreme events
- (3) Improvements of methods for describing the distribution of rainfall in time within storms
- (4) Establishing objective drought criteria and improving methods of characterising dry periods, their frequencies and durations.

6.5 OTHER TOPICS

- (1) Evaluating whether or not rainfall can be profitably stimulated
- (2) Determining whether environmental changes modify precipitation regimes
- (3) Development of remote sensing techniques of measurement and telemetry

- (4) Improvement of methods of quality control of data, storage and retrieval.

It might be argued that most of these topics are being currently researched and that solutions are near in many cases. Nevertheless considerable efforts are still required in these fields, hence the continuing interest of IASH in precipitation is a worthwhile function of the Association.

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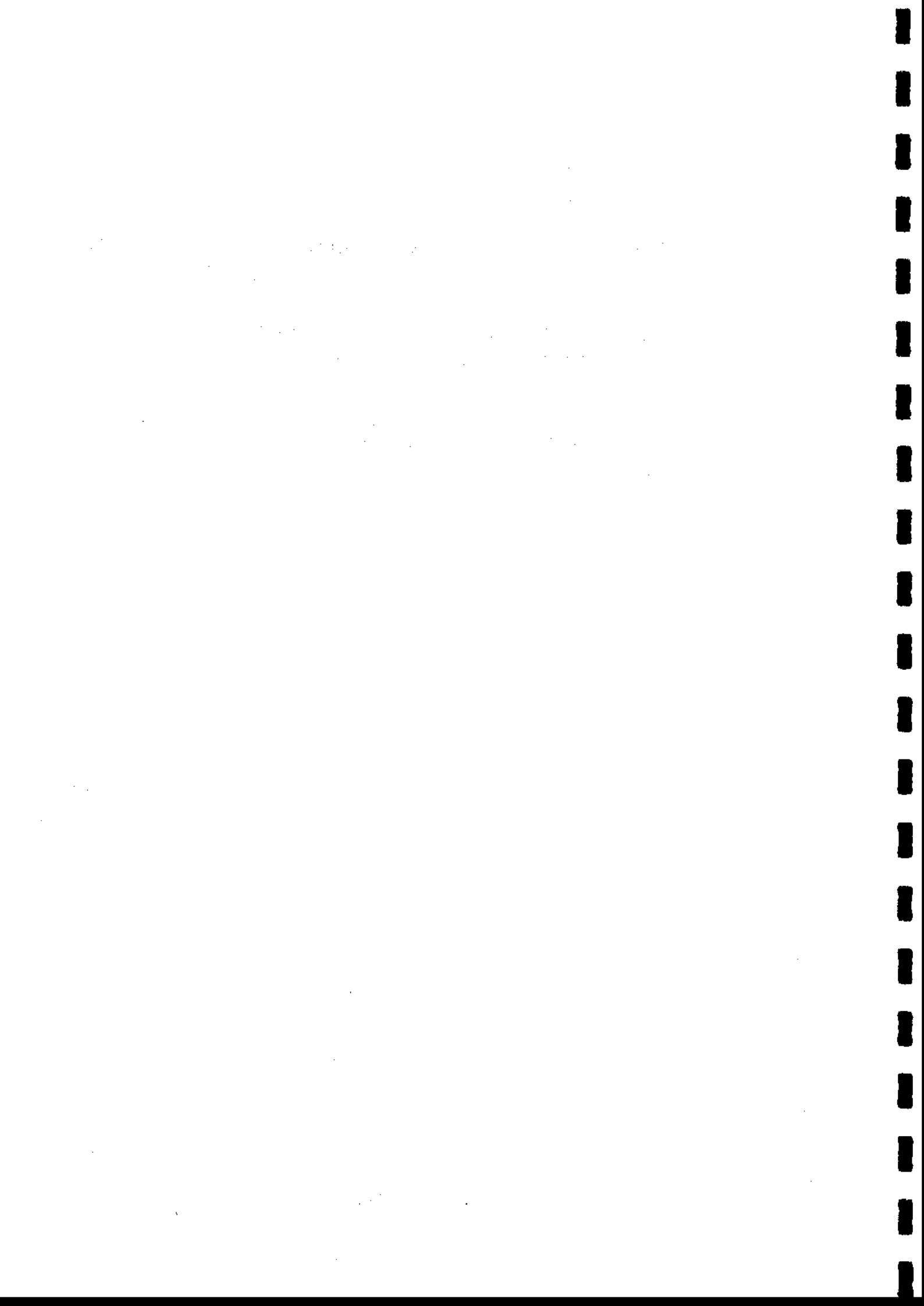
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